Norton-Thevenin Receptance Coupling (NTRC) as a Payload Design Tool

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Agenda

- Background
- Methodology
- NESC Study
- Future Work
- Summary

Acknowledgement

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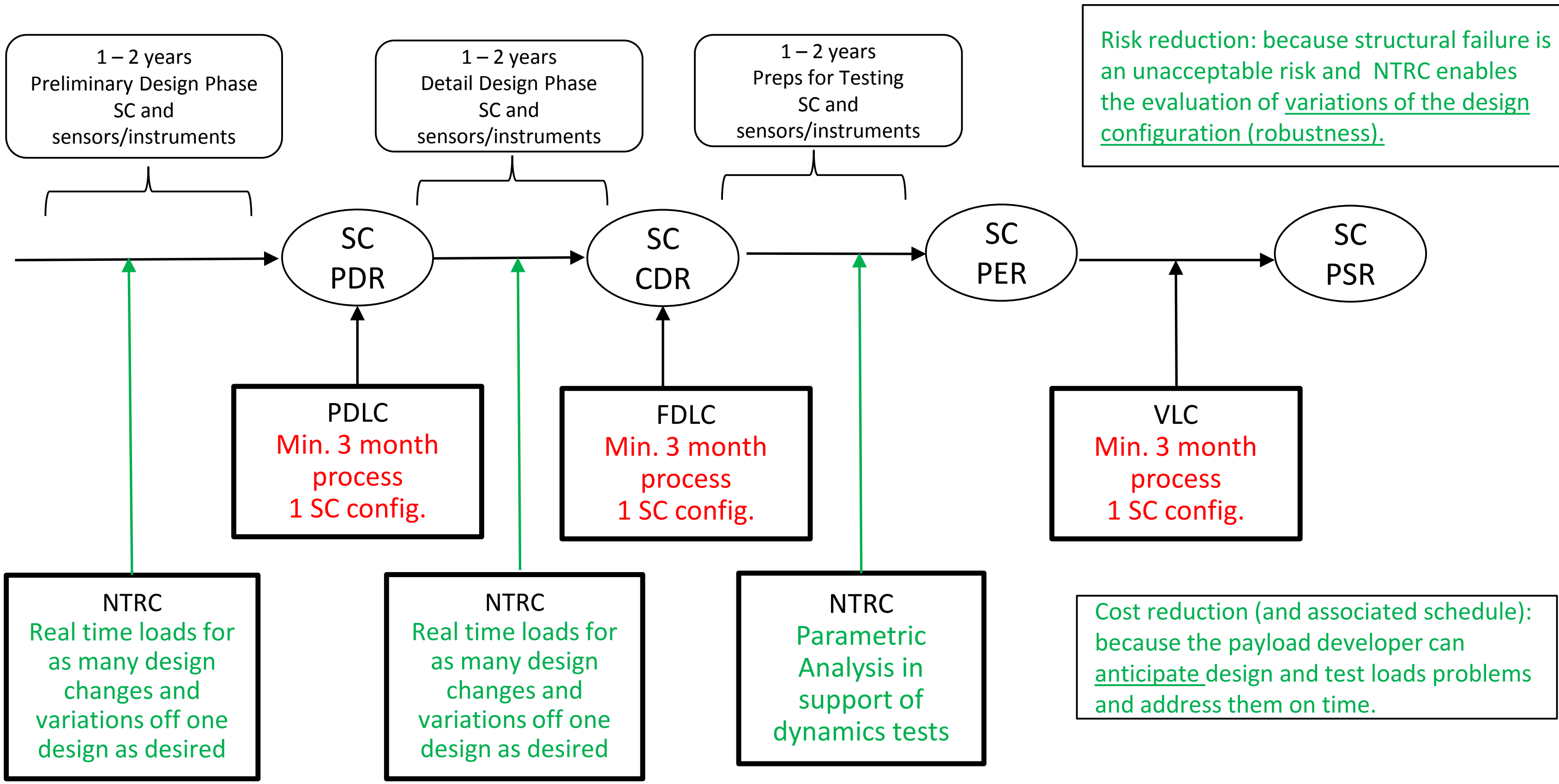
What is NTRC?

- NTRC combines receptance coupling methods with Norton-Thevenin Theory
- Receptance coupling = A method of coupling dynamic structures based on frequency response function (FRF) measurements/analysis
- Norton-Thevenin Theory = An interface impedance-based method for simulating the interaction between dynamic systems
- Allows for the behavior of the coupled system to be derived from measurements at the boundary of the two systems to be coupled
- Does not require launch vehicle models or forcing functions
  - Unloaded launch vehicle accelerations at interface (free acceleration)
  - Launch vehicle interface impedance (accelerance)

Why Was NTRC Developed?

- There is a need for a design tool that the LV payload community can use to estimate launch loads
- Limited methods for preliminary estimates of launch loads for subsystems and components
  - MAC/MMAC
  - Base-drive
- Payload community has limited access to CLA during life of a program (Typically 2 to 3 cycles)
  - Difficult to address design change that occur between load cycles
  - Difficult to assess impact of “as-built” hardware
- Allow payload community to assess launch loads with minimal amount of information required from the launch vehicle provider
- Not intended to replace the formal load cycles!

Typical Payload Development Process



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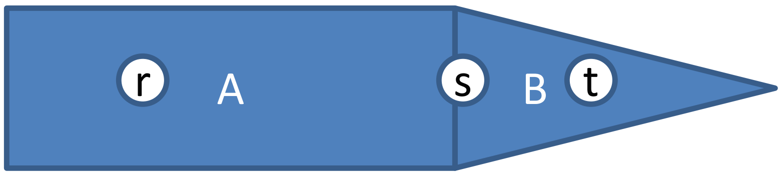
Benefits of NTRC

- Provides the payload community with ability to define/assess launch loads before and between official CLA cycles
- Operates on the minimum possible set of coordinates (equal to boundary DoFs) to solve the CLA problem, which improves solution times
- Solves in the frequency domain which allows for faster execution
- Allows for parametric analysis and trade-studies to optimize structural design and limit surprises from official CLA results [4]
- May provide benefit to the LV community
  - Faster response times for evaluating multiple payload configurations than standard CLA
  - Improved assessment of CLA models/forcing functions against measured flight data

NTRC Methodology



C: coupled system (A+B)
A: source with internal dofs r
B: load with internal dofs t
s: connecting dofs
H: accelerance [g/lb]
W: Impedance [lb/g] = H^{-1}
F: [lb], A: [g]

Coupled System Accelerance [3]

$$\begin{bmatrix} A_{Cr} \\ A_{Cs} \\ A_{Ct} \end{bmatrix} = \begin{bmatrix} H_{Crr} & H_{Crs} & H_{Crt} \\ H_{Csr} & H_{Css} & H_{Cst} \\ H_{Ctr} & H_{Cts} & H_{Ctt} \end{bmatrix} \begin{bmatrix} F_{Cr} \\ F_{Cs} \\ F_{Ct} \end{bmatrix} \qquad (1)$$

CLA: $F_{Cs} = F_{Ct} = 0$

From (1) :

$$A_{Cs} = H_{Csr} \; F_{Cr} \qquad (2)$$

$$A_{Ct} = H_{Ctr} \; F_{Cr} \qquad (3)$$

$\mathbf{H_{Xyz}}$ = Accelerance for System X with response at y dofs due to forces applied at z dofs

NTRC Methodology (Cont)

Receptance (Accelerance) Coupling for two substructures [3]:

$$\begin{bmatrix} H_{Crr} & H_{Crs} & H_{Crt} \\ H_{Csr} & H_{Css} & H_{Cst} \\ H_{Ctr} & H_{Cts} & H_{Ctt} \end{bmatrix} = \begin{bmatrix} H_{Arr} & H_{Ars} & 0 \\ H_{Asr} & H_{Ass} & 0 \\ 0 & 0 & H_{Btt} \end{bmatrix} - \begin{bmatrix} H_{Ars} \\ H_{Ass} \\ -H_{Bts} \end{bmatrix} \left[H_{Ass} + H_{Bss}\right]^{-1} \begin{bmatrix} H_{Ars} \\ H_{Ass} \\ -H_{Bts} \end{bmatrix}^T \quad (4)$$

From (4) we can define H_{Csr} and H_{Ctr} as:

$$H_{Csr} = \frac{H_{Bss}\, H_{Asr}}{H_{Ass} + H_{Bss}} \quad (5)$$

$$H_{ctr} = H_{bts}[H_{ass} + H_{bss}]^{-1} H_{asr} \quad (6)$$

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NTRC Methodology (Cont)

Rewrite (2) using (5):

$$A_{Cs} = [H_{Csr}]F_{Cr} = \frac{H_{Bss}\, H_{Asr}}{H_{Ass} + H_{Bss}}\ F_{cr} \qquad (7)$$

Rewrite (3) using (6):

$$A_{Ct} = [H_{Ctr}]F_{Cr} = H_{Bts}\,[H_{Ass} + H_{Bss}]^{-1} H_{Asr}\ F_{Cr} \qquad (8)$$

Combine (7) and (8):

$$A_{Ct} = H_{Bts}\ H_{Bss}^{-1} A_{Cs} \qquad (9)$$

Introduce Norton-Thevenin [1] to relate the free acceleration (A_{As}) to the coupled acceleration at the boundary:

$$A_{Cs} = [H_{Ass}^{-1} + H_{Bss}^{-1}]^{-1} H_{Ass}^{-1} A_{As} \qquad (10)$$

Combine (9) and (10) to get desired expression of coupled payload response (A_{Ct}) as a function of LV free acceleration (A_{As}):

$$\boxed{A_{Ct} = H_{Bts}\ H_{Bss}^{-1}\,[H_{Ass}^{-1} + H_{Bss}^{-1}]^{-1} H_{Ass}^{-1} A_{As}} \qquad (11)$$

NTRC Time Domain Analysis

One implementation of Equation (11)

- NTRC is a frequency domain analysis technique
- FFT/IFFT processing is used to perform NTRC in the time domain
- Steps
  1. Perform transient analysis on LV to derive the free-acceleration (A_{As}) at payload interface
  2. Transform A_{As} to frequency domain via FFT. Extract positive frequency terms and remove the f=0 Hz term (save for later)
  3. Calculate accelerance (H) for payload and launch vehicle at common interface (consistent frequency range and delta-f).
  4. Derive NTRC transform and convert A_{As} to the coupled system interface acceleration (A_{Cs}) in the frequency domain

$$A_{Cs} = [H_{Ass}{}^{-1} + H_{Bss}{}^{-1}]^{-1} H_{Ass}{}^{-1} A_{As}$$

  5. Use IFFT to transform A_{Cs} back to the time domain (w/ f=0 term from FFT of A_{As})
  6. Basedrive PL with A_{Cs} to recover internal responses

NESC Study

- Study approved December 2015, started January 2016
- NESC approved the funding for a 1year study with effort broken into Quarters
  - Quarter 1 = Frequency domain
    - Heavy payload
    - Determinate and indeterminate interfaces (24 DoFs)
    - Multiple payloads
  - Quarter 2 = Time domain (no steady-state)
    - FFT/IFFT processing
    - LV/Payload model truncation w/ residual vectors
  - Quarter 3 = SLS/Europa + non-linear pad separation study
    - SLS/Europa with in-house forcing functions (no steady).
    - Highly indeterminate interface (144 DoFs)
    - In-house pad separation models and non-linear liftoff simulations
  - Quarter 4 = Liftoff CLA
    - Use in-house non-linear simulation developed in Q3 for benchmarking
    - Liftoff pad sep with initial conditions and quasi-steady content
    - Delta IIH/GLAST [3]
- Additional Q5 Funding Added to benchmark against SLS liftoff and complete final report (Estimated Completion – August 2017)

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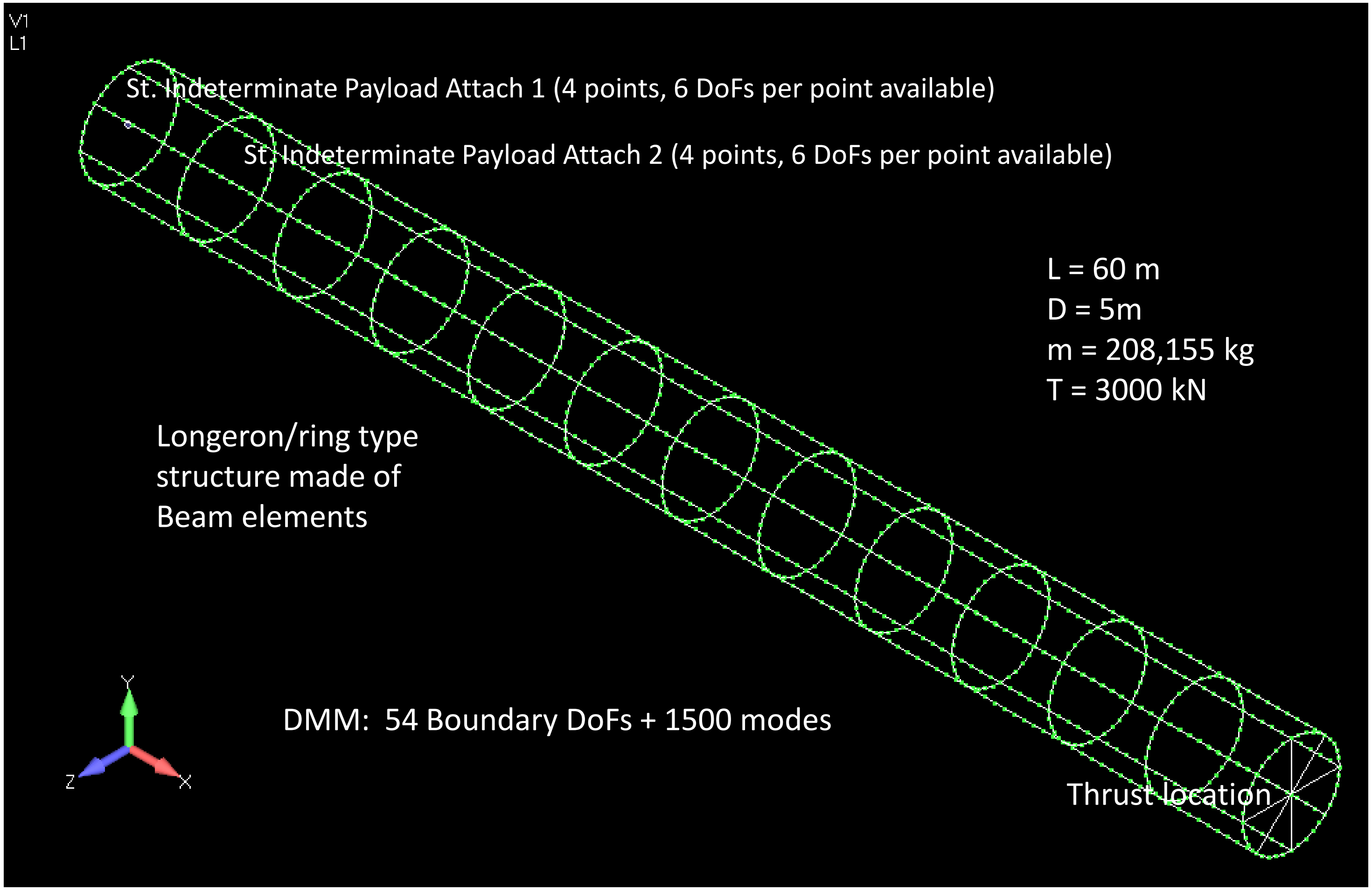
Launch Vehicle FEM



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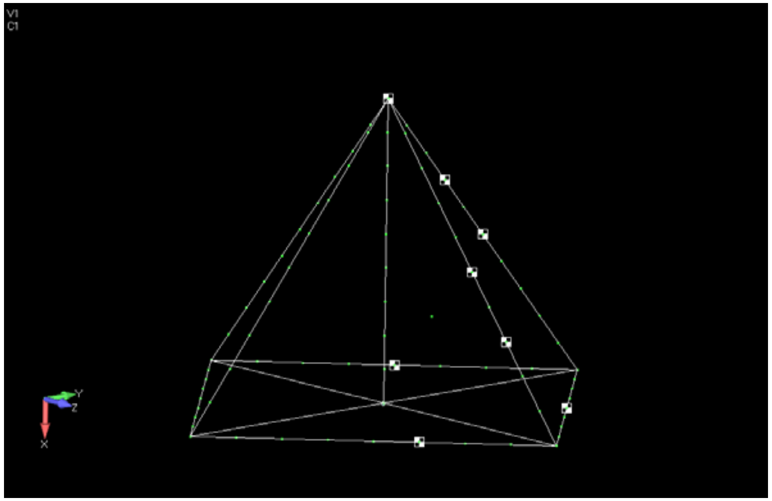
Heavy Payload FEM



- Heavy payload FEM constructed to meet following requirements:
  - Weight: 3717 kg (8177 lbs)
  - Off-axis CoG
  - 1^{st} lateral/rocking frequency 10-20 Hz (FEM: 10.6 Hz)
  - 1^{st} axial frequency 20-40 Hz (FEM: 31.6 Hz)
    - All frequencies wrt st. det. constraints
- DMM: 24 physical DoFs + 200 modes
- Acceleration and Stress Transformation Matrices (ATM, STM) generated for internal response computations

NTRC Reminders

- Operates on LV free accelerations/accelerance at payload interface
  - No mass loading of interface required
  - Calculate LV free accelerations one time for multiple payload configurations
- Operates on the minimum possible set of coordinates to solve CLA problem. For in-house LV + PL example:
  - NTRC = 24 DoFs
  - CLA = 1554 + 224 – 24 = 1754 DoFs
- Solves in frequency domain
  - Fast executions

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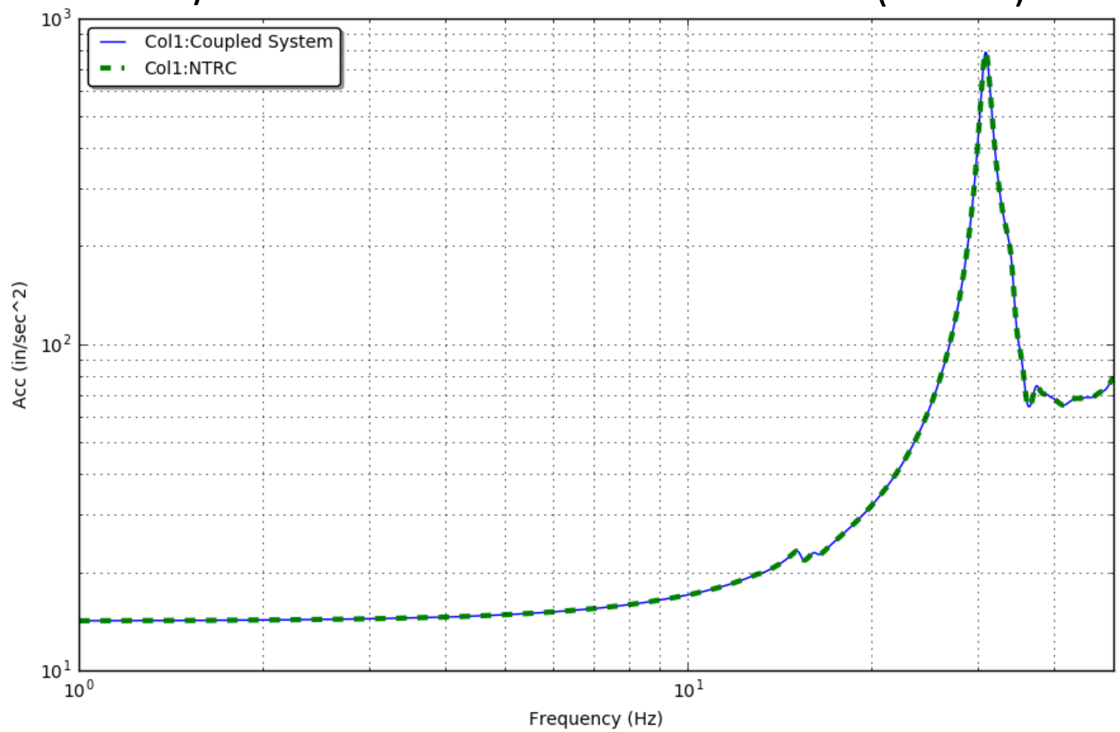
Frequency Domain Results

- NTRC in the frequency domain is exact
- Results match within numerical accuracy of analysis
- All Hurty Craig-Bampton (HCB) modes must be used **or**
- Free-free modes must be augmented with residual vectors

I/F Acceleration – DOF 10000001-1 (Thrust)



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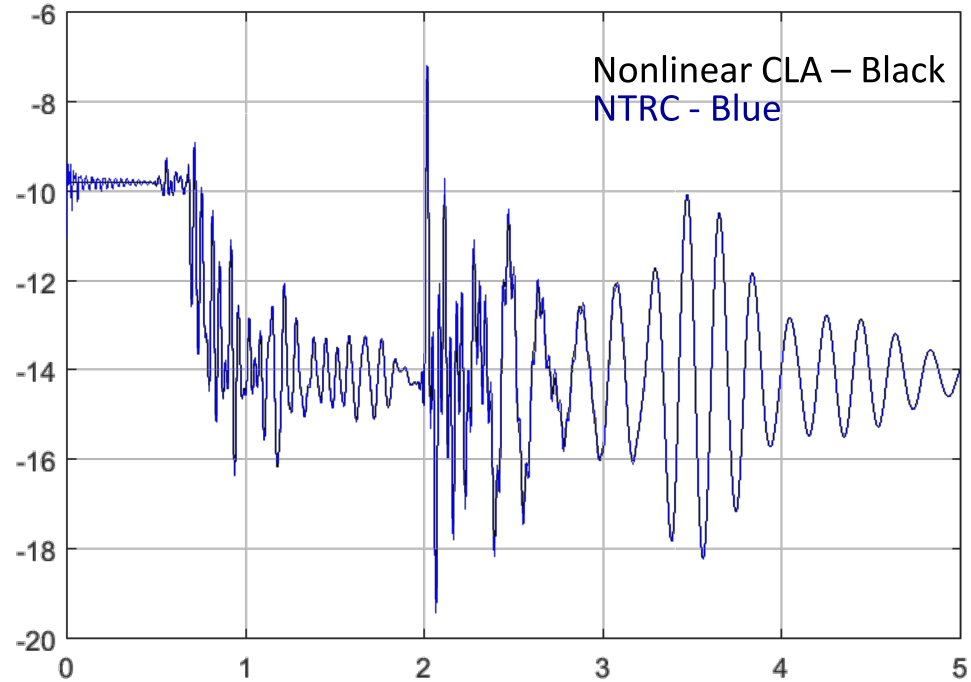
NTRC Time Domain Results

- NTRC results captures all relevant characteristics of a transient CLA
- NTRC matches CLA w/o steady-state to < 5%
- Time domain NTRC with steady-state matches CLA < 5% for significant payload responses
- Source of differences
    - Convergence of time domain analysis
    - FFT/IFFT processing
- Will continue to refine time domain analysis for Q5 activities (SLS)

I/F Acceleration – DOF 10000001-1 (Thrust)



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Items Addressed During NTRC Study

- Development of NTRC routines in Python
- Damping for free-free and HCB modes
- Use of residual vectors to address modal truncation
- Use of free-free vehicle modes for non-linear pad separation analysis
- Development of methodology to address transient analysis with steady-state
- Identification of time history artifacts(ringing) created by FFT/IFFT process and possible solution schemes.

Upcoming Activities

- Benchmarking (Q5)
  - SLS + Europa Clipper - Liftoff
  - Delta II + GLAST – Liftoff and Airloads
- Release NESC report

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Summary

- NTRC is an alternate coupling approach that can be used to replicate a standard LV CLA
- NTRC developed as a design tool for payload community with the minimum information required from LV providers
- NTRC is exact for frequency domain analysis
- NTRC shows excellent agreement with results from time domain CLA
- Completion of SLS liftoff benchmarking and release of final report expected August 2017